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Liquid crystal electrography: Electric field mapping and detection of peak electric field strength in AlGaN/GaN high electron mobility transistors ☆

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ABSTRACT

The liquid crystal mixture E7, based on cyanobiphenyl, has been successfully employed to map electric field strength and distribution in AlGaN/GaN high electron mobility transistors. Using a transmitted light image through crossed polarizers the optical response of the liquid crystal deposited onto the surface of the devices was recorded as a function of source–drain bias, V_{ds}. At a critical voltage of 4 V the preferred direction of orientation of the long axes of the liquid crystal molecules in the drain access region aligned with one of the polarizers resulting in reduced transmitted light intensity. This indicates that at this electric field strength molecule orientation in most of the liquid crystal film is dominated by the electric field effect rather than the influence of surface anchoring. The experimental results were compared to device simulations. Electric field strength above the surface at V_{ds} = 4 V was simulated to reach or exceed 0.006 MV/cm. This electric field is consistent with the field expected for E7 to overcome internal elastic energy. This result illustrates the usefulness of liquid crystals to directly determine and map electric fields in electronic devices, including small electric field strengths.

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have been the focus of intensive research to deliver improved device reliability in recent years [1]. Their wide bandgap makes them an excellent candidate for high power applications giving improved performance in power-supplies as well as radar or satellite systems. Many aspects of the reliability and operation of these devices are still not very well understood or solved, including the underlying physics of electronic trapping sites within the bulk of the devices [2,3] or within surface leakage paths [4]. In addition, the physical origin of device degradation during operation is still controversial [5,6]. Devices exhibit high internal electric fields and high channel temperatures, well in excess of traditional semiconductor device systems. These can trigger degradation and generation of electronic traps [7]. Investigation techniques employed have included electrical methods [8,9] such as pulsed IV or transient analysis [10,11] as well as optical methods such as electroluminescence [12]. These traps impact device performance including a reduction in source–drain current or can lead to higher leakage currents along interfaces and at the device surface. Typically field plates or gate shaping are used to limit the maximum electric field present in the devices [7]. While accessing temperature in the devices is nowadays easily possible for example using Raman, infra-red or liquid crystal thermography [13–15], quantifying experimentally peak electric fields that drive electronic trap generation and device degradation is challenging. Past efforts have used Kelvin probe force microscopy [16] as well as depth-resolved cathodoluminescence spectra [17] to try to correlate local electric field strength with degradation phenomena due to material defects and stress-induced traps. While liquid crystals have been used in the past to image temperature distribution and hot spots in the devices [18] their potential to image electric fields in electronic devices has been ignored to date. This is despite their wide scale use in displays that exploit their orientation under an electric field [19]. Several different phases of low or high order can be achieved in a liquid crystal depending on temperature or the presence of external electric fields [20]. In this work it is demonstrated that liquid crystal can be used for electric field analysis of electronic devices, on the example of AlGaN/GaN HEMTs. This is done by using their ability to orientate with electric field lines in the nematic phase rather than exploiting a phase change.

2. Experimental details

HEMTs fabricated from a 25 nm AlGaN barrier on a 1.9 μm thick GaN layer grown on an insulating SiC substrate were studied. The

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devices were passivated with 325 nm of Si_3N_4. Si_3N_4 is a commonly used layer in the devices to control traps at the surface and device leakage currents [21]. This entire material stack is transparent under white light illumination, apart from areas covered by metal contacts. Source–gate spacing and drain–gate spacing were 1 μm and 2.4 μm, respectively, with a gate length of 0.6 μm and a gate width of 100 μm. Liquid crystal of type E7 were deposited on the HEMT device surface with E7 containing 51% 5CB (cyanobiphenyl), 25% 7CB (cyanobiphenyl), 16% 8OCB (octyloxy-cyanobiphenyl) and 8% 5CT (cyanoterphenyl) [22]. The individual molecules within the mixture have lengths of around 2 nm and demonstrate the nematic phase at a temperature of up to 58 °C. Even though the individual molecules are disordered in the nematic phase, the long axes (as illustrated in Fig. 1C) have a preferred direction. This direction is represented by the director and the material is birefringent. [23] The devices were operated up to a source–drain voltage of 20 V with a gate bias of −6 V. Operating the device under pinch off conditions avoids any significant heating effects. Gate leakage current in the device considered here was less than 0.3 mA/mm. The devices were imaged using an optical microscope with a 50*x*, 0.7 numerical aperture objective, under crossed polarizers with backlight white illumination to record the optical response of the liquid crystal molecules under the electric field in the devices. A schematic of the experimental setup is shown in Fig. 1. For the deposition of the liquid crystal on the AlGaN/GaN HEMT, it is important to achieve a thin layer to avoid convective instabilities [23], which may be caused by temperature or leakage currents. On the other hand, a thin layer on the scale of the dimensions of the liquid crystal molecules would result in alignment dominated by the surface structure or the homeotropic anchoring at the air–liquid crystal interface. For best results a layer below 10 μm was applied, which was found to be thin enough to avoid convective instabilities. This was achieved by applying a droplet of liquid crystal using a needle with the liquid crystal flowing onto the surface of the device due to surface tension, rather than spin-coating. This thickness is consistent with commercially used liquid crystal films for displays [19].

3. Results and discussion

Fig. 2 shows transmitted white light images of the access region for a device at increasing source–drain voltages, V_{ds}, all in pinch-off condition (V_{gs} = −6 V), i.e. no current flow. As the light reaching the camera must pass through crossed polarizers, it can only pass if the optic axis of the nematic is not parallel to either polarizer when no bias is applied to the device. As parts of the device surface are covered by metal contacts only the source–drain access region is visible in the images in Fig. 2. A decrease in light intensity with the increased applied source–drain bias, i.e. with increasing electric field strength, is visible. This decreasing light intensity with applied bias demonstrates the optical response of the orientation of the liquid crystal director, which aligns parallel to the applied electric field and therefore one of the polarizers if enough energy is provided to overcome the effect of surface anchoring of the liquid crystal molecules. As we are operating the device in pinch off no significant heating will affect the liquid crystal film and the darkening of the transmitted light image can be fully attributed to director alignment rather than a phase change in the liquid crystal.

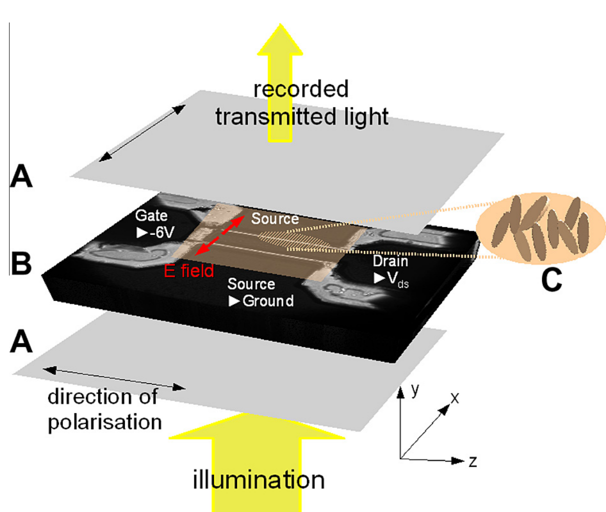

Fig. 1. Schematic set up of measurements showing (A) crossed polarizers with (B) the two gate finger device positioned in between and (C) a representation of liquid crystal.

The electric coherence length, ξ_E, [24–26], describes the thickness over which the director orientation is dominated by the elastic forces. Elasticity tends to maintain the director parallel to the surface anchoring. As it is inversely proportional to the electric field strength, it is expected to decrease with increasing source–drain voltage, V_{ds}. A small ξ_E means that only the molecules closest to the device surface will be forced to stay orientated according to surface anchoring leaving the rest free to orientate with the applied electric field. As the electric field is applied parallel to the direction of polarization of one of the polarizers (Fig. 1), alignment of the director with the electric field results in reduced transmitted light. Minimum brightness is achieved when the electric field is sufficiently strong to decrease the value of the electric coherence length to a value that is significantly smaller than the applied liquid crystal film thickness. For an electric field strength of 0.006 MV/cm ξ_E is about 1.6 μm reaching a sub-micron value at an electric field strength of 0.01 MV/cm. We note, the device's own birefringence means that the cross-polarized arrangement always lets some light pass, i.e. even under maximum director alignment (Fig. 2c and d) the images do not become completely dark. Fig. 3 illustrates the average transmitted white light intensity in the active device region as a function of source–drain bias. The intensity values are stated as a fraction of the transmitted light intensity for an unpowered device. The gradual decrease of transmitted light intensity demonstrates the gradual decrease of the electric coherence length. At a source–drain bias of around 4 V (Fig. 2c) the applied electric field dominates over the elastic forces within the liquid crystal and the director is orientated along the direction of polarisation for most of the liquid crystal film. A further increase of the applied voltage, i.e. electric field strength, produces the same director alignment, i.e. the brightness of the images does not decrease any further. As there is no temperature rise in the devices, all changes observed are clearly related to the presence of an electric field in the region where the liquid crystal is situated.

Drift diffusion simulations of the AlGaN/GaN HEMT were performed using Silvaco ATLAS to determine the strength of the electric field at the critical voltage that resulted in reorientation of the majority of the liquid crystal molecules with the electric field. Fig. 4 shows the result of the simulation at a source–drain voltage of 3 V, slightly below the experimentally observed voltage of director alignment of 4 V. Fig. 4a considers the typical scenario of air above the Si_3N_4 passivation while Fig. 4b shows the experimental case with the liquid crystal on top of the Si_3N_4 passivation. The liquid crystal layer was simulated up to a thickness of 3 μm as the electric coherence length will lie within this thickness. Liquid crystal molecules above this thickness will be able to orientate freely with an external applied field due to the absence of a strong surface anchoring effect of the underlying hard surface and hence have no strong impact on the observed effect. The weak boundary